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August 1987
NSRP 0281

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1987 Ship Production Symposium

Paper No. 17: Novel Techniques and Their Applications for Measuring Out-of-Plane Distortion of Welded Structures

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1987**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **The National Shipbuilding Research Program 1987 Ship Production Symposium Paper No.17: Novel Techniques and Their Applications for Measuring Out-Of-Plane Distortion of Welded Structures**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center CD Code 2230 - Design Integration Tools Building 192 Room 128 9500 MacArthur Blvd Bethesda, MD 20817-5700**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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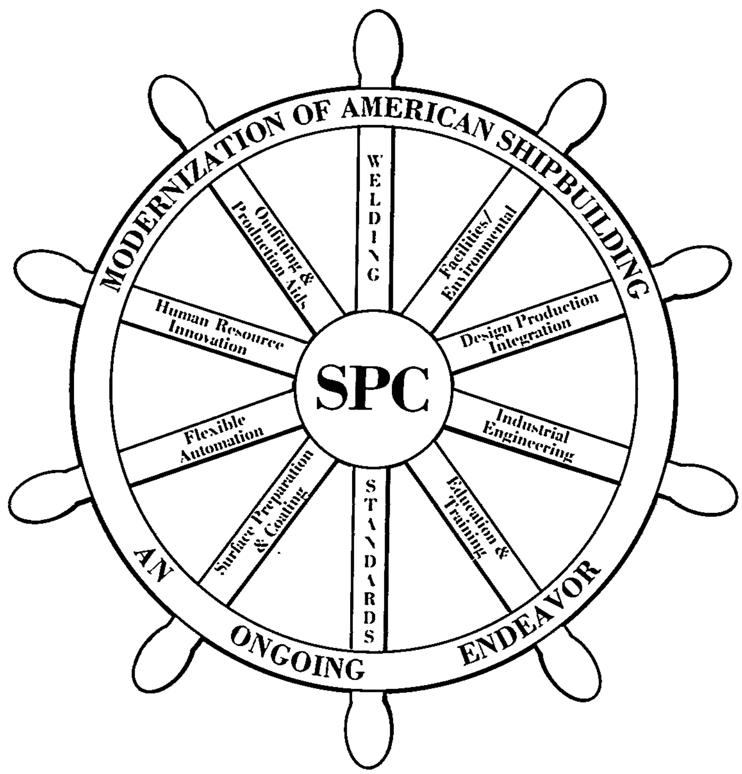

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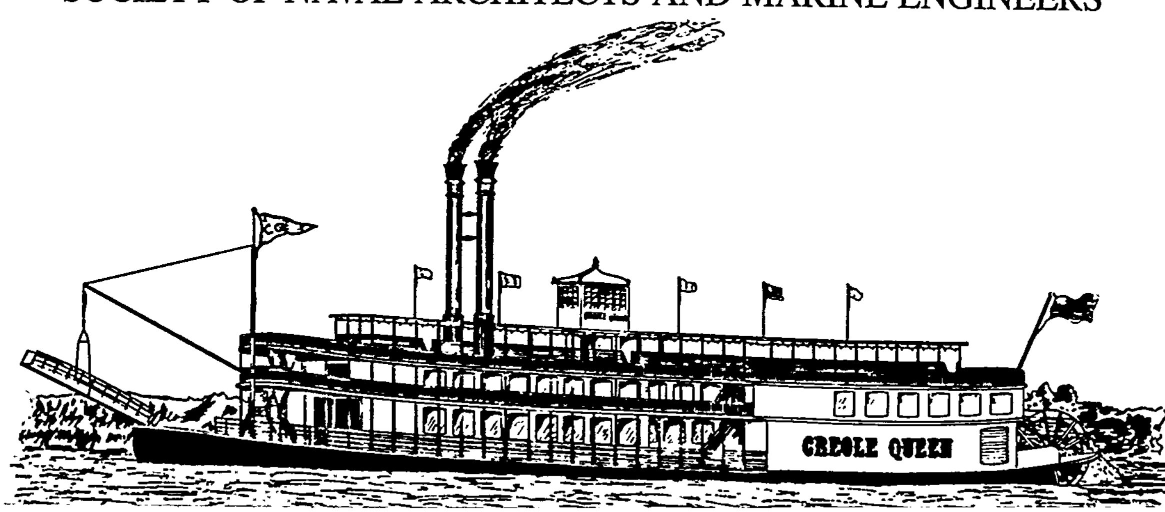

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS
601 Pavonia Avenue, Jersey City, NJ 07306
Paper presented at the NSRP 1987 Ship Production Symposium, Hyatt Regency Hotel, New Orleans, Louisiana, August 26-28, 1987

Novel Techniques and Their Applications for Measuring Out-of-Plane Distortion of Welded Structures

No. 17

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ABSTRACT

Whether or not a certain amount of planar distortion is critical, a point of consistency in the ship fabrication process is the need to accurately assess an existing degree of distortion in both local and global domains. At the Massachusetts Institute of Technology, three novel measurement devices have been developed as an adjunct to ongoing research. Distortion can now be evaluated either through laser interferometry, low-power laser beam triangulation, or direct surface contact. In addition to describing the operation and construction of the devices, their particular applications from a ship production/plate forming perspective are detailed.

NOVEL TECHNIQUES AND THEIR APPLICATIONS FOR MEASURING OUT-OF-PLANE DISTORTION OF WELDED STRUCTURES

Introduction

How bent is bent? The answer to this question has been important to shipbuilders and designers for centuries. And today, as newer materials and fabrication techniques are introduced, possibly with more stringent fit-up tolerances, it may be of even greater significance. The objective of this discussion is to introduce several new measurement techniques which may ultimately assist those in the shipbuilding industry who are dealing with such a question.

"Distortion," from the perspective of this paper, is considered to be the degree a shape may vary from its intended form. In the extreme case, this can range from a complex-contoured section of hull plating to the planar characteristics of a main deck or bulkhead. With the former, a precise amount of bending is required; with the latter, complete absence of bending becomes the ideal. clearly, "distortion" in shipbuilder parlance may be a welcomed or damned phenomenon.

Whether or not a certain amount of distortion is critical at a particular location onboard ship, a point of consistency in the fabrication process is the need to accurately assess the state of bending in both local and global domains. Such assessment could be performed for individual plates prior to join-up, in situ for checking overall section contours, for post-weld distortion removal activities, or conceivably as part of an effort to quantify post-collision hull damage.

Over the past few years, a significant amount of research at the Massachusetts Institute of Technology (MIT), under the tutelage of Professor Koichi Masubuchi, has been devoted to studying weld distortion phenomena as well as thermo-mechanical plate bending techniques using laser line heating(l,2). Although the end objectives of each project differed markedly, they all shared a common need for rapid, reliable, and accurate distortion assessment (measurement) in the laboratory. Complementing the main thrust of each study was the concomitant development of devices which could satisfy such measurement requirements. Based on this work, distortion may now be evaluated either through laser interferometry, low-power laser beam triangulation, or direct surface contact.

Scope

This paper presents alternate applications for three MIT distortion measurement methods from the standpoint of ship production and repair. Since the measurement technique involving laser interferometry was previously reported at the Spring Meeting of the Society of Naval Architects and Marine Engineers (SNAME) in 1985 (3), only a summary is provided here for completeness. Regarding the remaining devices, the discussion will concentrate on design considerations, principles of operation, brief hardware/software descriptions, attendant measurement results, and their current state of development

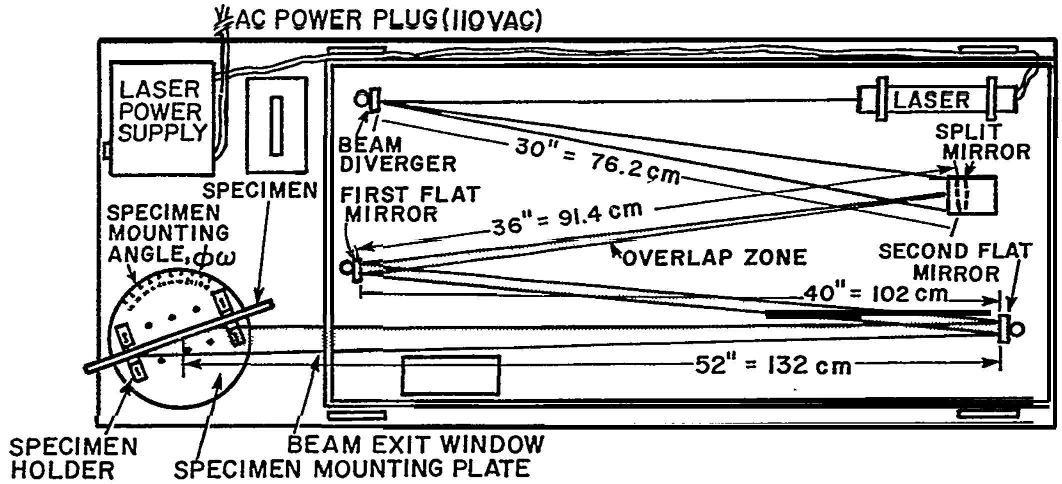


Fig. 1 Laser Interferometer developed at MIT (top view)

Measurement Method #1: Laser Interferometer (Summary)

Interferometry measurement involves the use of constructive and destructive interference among waves of light emitted from a single source. With the present arrangement, and as depicted in Figure 1, a 10 milliwatt, helium-neon laser serves to provide an intense, monochromatic beam of light which is expanded, columnated, and split into two phase-locked overlapping beams. Beam geometry is shown in Figure 2. Because of the overlap, a system of parallel interference fringes composed of alternating bright and dark vertical lines will appear on a diffused surface placed anywhere in the overlap zone.

Measurement of out-of-plane distortion is accomplished by interpretation of an illuminated specimen's fringe patterns. When the specimen is not flat, the interference fringe pattern is distorted; the nature and the amount of such fringe distortion thus details specimen distortion.

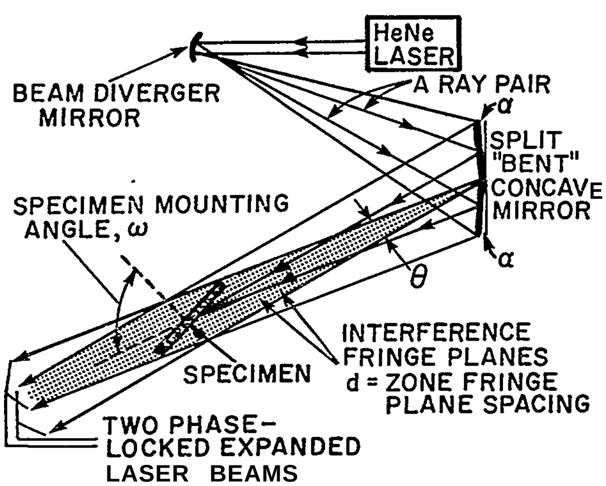


Fig. 2 Laser Interferometer optics

A sample fringe pattern on a fillet weld specimen appears in Figure 3. Although not detailed here, equations have been developed which enable the operator to quantify local specimen distortion based on corresponding fringe distortion.

Depending on the orientation of the phase-locked light and the specimen, a change in the fringe pattern may show longitudinal bending, lateral bending, or contour deformation which may exist, for example, along a typical fillet weld. Changes in specimen surface elevation within 5 ten thousandths of an inch (0.0005") can be detected with the laser interferometer developed at MIT.

Although laser interferometry may be considered a non-contact measurement method, specimens with metallic surfaces should first be optically diffused with a thin layer of spray paint to reduce glare and enhance fringe definition. Ideally, no surface obstructions should be present, since their shadows could mask important contour changes. Specimens must also be fairly smooth, and free from deep pits or corrugations.

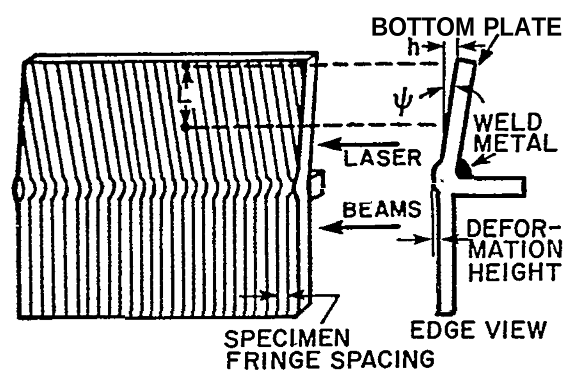


Fig. 3 Fringe pattern observed on the back surface of a fillet weld having both contour and lateral bending distortion

Based on the intensity of the laser light source, the ambient light level must be low enough to observe specimen fringes. Additionally, fringe pattern stability will also depend on minimal air convection currents at the specimen surface as well as a vibration-free environment for both the specimen and interferometer.

Reference (1) provides the background, theory, and sample calculations required for distortion analysis using the MIT laser interferometer. Also discussed are photographic and video camera recording procedures used to examine fringe patterns changes both during and subsequent to welding sequences.

The following two methods were developed to support present research concerning automated thermo-mechanical bending of steel plates using laser line heating. Consequently, the devices were conceptualized from a need to assess plate-wide specimen distortion which would be difficult using interferometry. As will become obvious, their use may be easily extended to measurements in three dimensions over large surface areas if required by an industrial facility.

Measurement Method #2: Non-Contact Distortion Measurement Using Low-Power Laser Beam Triangulation

Motivation. Because of the complexity involved in thermo-mechanical plate bending, especially in lieu of human expertise in the process, dependency on computer-assisted monitoring and control is presently considered essential. A natural progression toward evaluating the feasibility of fully automated plate forming was the development of a measuring subsystem which could be computer integrated with distortion prediction algorithms, laser pass sequencing logic, plate speed and laser power controls, etc. To achieve technological harmony among all critical components and interfaces, elimination of the human element in distortion measurement and feedback was adjudged fundamental. Further, from the standpoint of mechanical simplicity and to minimize interference with the optical laser path, etc., a non-contact type of measurement seemed most viable.

Design Considerations. Because of its anticipated role in an “automated” environment, the non-contact distortion measurement device (NCMD) to be described was envisioned to operate in at least a semi-permanent location as a plate forming system component. Implicit in this respect was an assumed specimen orientation. Given this scenario, seven additional requirements were specified.

1. Accurate Local Distortion Measurement. Plate distortions can range from a few thousandths of an inch to several inches depending on the desired contour and point of measurement. Consequently, the NCMD must be able to discern small changes in surface elevations as well as accept a broad range of possible elevations.

2. Rapid Measurement Process. Accurate measurement at the expense of delaying the process is not acceptable. This criterion included both set-up and actual measurement times, both of which would be critical in an automated environment.

3. Real-Time Availability of Results. As a corollary to the proceeding item, once a measurement procedure was performed, access to its outcome was desired on a near-instantaneous basis. Data conversion and subsequent availability within a few seconds were considered especially essential for in-process plate bending feedback.

4. “Negative or Positive” Distortion Measurement Capability. Considering general plate curvature, both concave terrains may coexist. Such conditions should be anticipated and accommodated without operator intervention.

5. Ease of operability. While analysis and use of measurement data may comprise a sophisticated portion of a bending prediction algorithm, design philosophy considered that obtaining the data should be a straight-forward procedure not requiring special expertise or training for the end user. From this perspective, acceptance of the NCMD would be enhanced at the worker level and training expenditures minimized.

6. Durability. The device was expected to find use in an industrial environment. Susceptibility to temperature fluctuations, dust, electromagnetic and infrared radiation, rough handling, etc., was probable.

7. Economy in Design. One of the most fundamental of all design decisions, this factor was assumed to apply not only to initial development of the new device but also to future industrial facility procurement and follow-on repair/maintenance requirements.

Principles of Construction and Operation. The triangulation method adopted in the NCMD design has the capability of measuring a vertical change in plate elevation above a horizontal reference plane by sensing a change in an established angular

relationship among system components. To develop the prescribed geometry, the device is positioned directly above a plate specimen. Although vertical separation between the prototype and a typical plate is approximately seven feet in the laboratory, this distance is not critical for proper operation. Presumably such a device could be mounted near or on the ceiling of the building where measurements are to be performed.

Referring to Figure 4, the essential geometry is detailed. **Angle θ is formed** by the reflection of a low-power laser beam between two mirrors and the plate specimen. The system's height above a horizontal reference plane, L, and the horizontal separation between mirrors, d, are fixed. Elevation above the plane, "delta Z", is determined from the following equation:

$$\Delta Z = L - (d)(\tan \theta).$$

The value of angle θ in the equation is known based on mirror motor position when the laser spot on the plate has been centered in the camera's optical image area. Of course plate thickness must be taken into account to determine actual plate distortion.

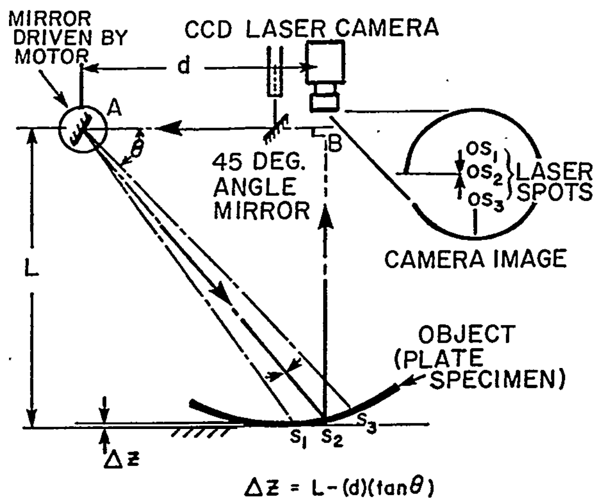


Fig. 4 Geometric principle of operation for the non-contact distortion measurement device

External to an IBM-compatible AT&T PC 6300 personal computer and the required component power supplies, the complete NCMD as designed consists of six pieces of hardware rigidly mounted to an aluminum frame. A perspective of their arrangement is provided in Figure 5. Figures 6-9 offer more detail. Individually, they include:

1. Low-power Helium-Neon Laser Assembly. Beam power is approximately 2 milliwatts; beam width is approximately 0.03 inches.

2. Precision Mirror Drive Motor and

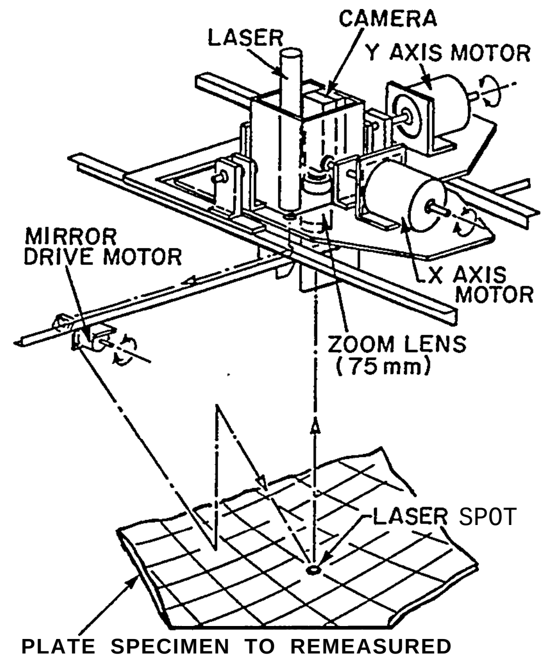


Fig. 5 Perspective of non-contact distortion measurement device hardware arrangement

Mirror. The angular position of this motor's drive shaft determines **the value of θ used in the above** equation. Angular resolution is 0.000251 radians (25,000 equal angular increments per revolution). The mirror is attached directly to the drive motor as shown in Figures 6 and 9.

3. Charge Coupled Device (CCD) Camera. Fitted with an adjustable zoom lens and a software-controllable aperture, the camera is used to detect reflection of the low-power laser spot from a specimen's surface. Laser spot position within the image area is determined by electronic measurement of intensity. The distance between the optical axis of the CCD camera and the mirror drive motor shaft determines the value of "d" in the distortion measurement equation above.

4. X-Axis Scanning Motor. For reference, a horizontal (x,y) Cartesian coordinate plane is assumed to be centered on each plate measured. The x-axis scanning motor repositions the rigid component frame so that elevations along the entire specimen axis can be determined. Figures 8 and 9 offer two views of this motor.

5. Y-Axis Scanning Motor. Although not installed in the present configuration, this component is an identical counterpart to the x-axis

motor except that it allows y-axis measurements. Correct sequencing of both motors affords plate-wide measurements and thus three dimensional representation of the specimen contours.

6. 45° Angle Mirror. Rigidly mounted directly below the low-power laser tube, this mirror simply redirects the beam toward the mirror/mirror drive assembly. Front and side views of this mirror are available in Figures 6 and 7.

Figure 10 is a "system view" of the NCMD at MIT. A laser formed dish-shaped steel plate is shown positioned for measurement.

Fig. 6 Frame assembly of non-contact distortion measurement device (Illustrates housing for helium-neon laser & CCD camera; mirror motor is visible in right foreground.)

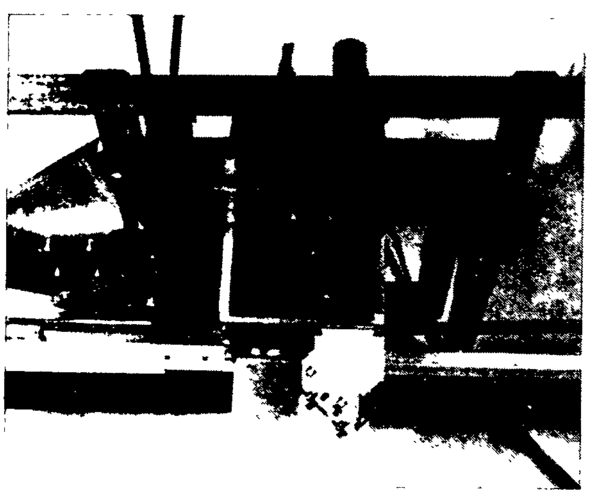


Fig. 7 Helium-neon tube and CCD camera mountings in frame assembly of non-contact distortion measurement device.

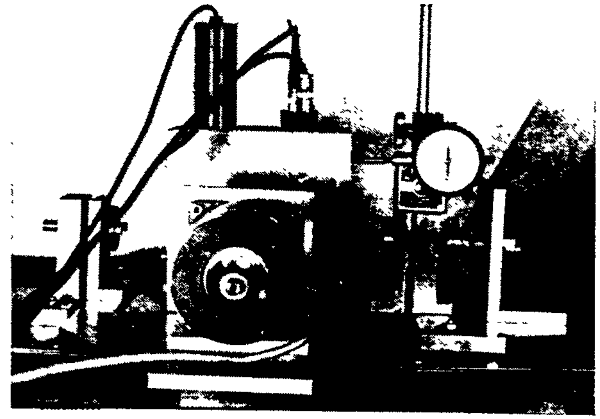


Fig. 8 End view of X-axis scanning motor attached to frame assembly of non-contact distortion measurement device.

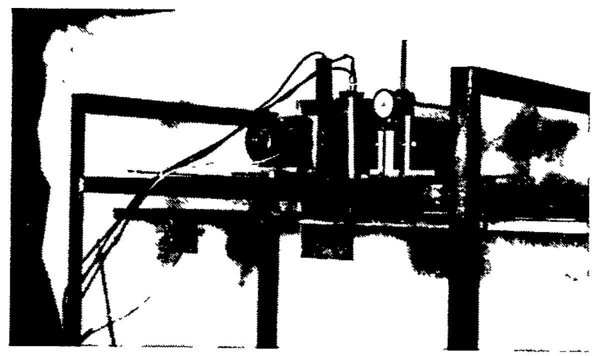


Fig. 9 View of frame assembly hardware for non-contact distortion measurement device. (Note mirror motor in left background and mounting bracket for Y-axis scanning motor in right foreground.)

Fig. 10 Plate specimen measurement with the non-contact distortion measurement device.

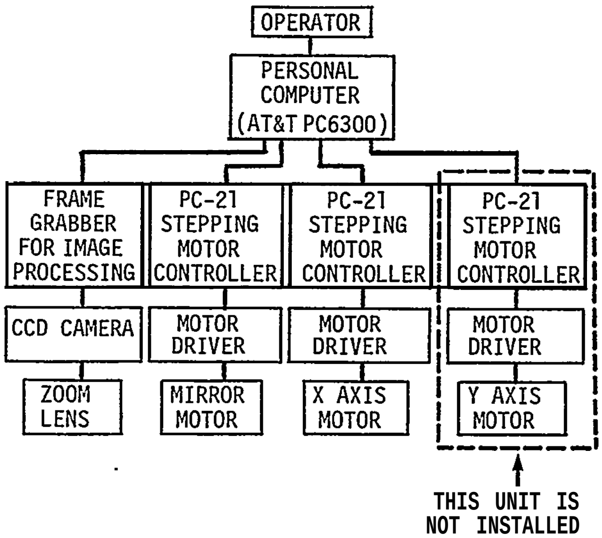
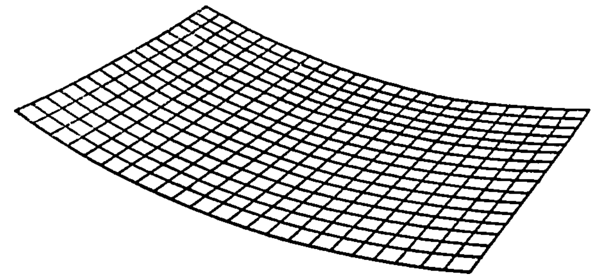


Fig. 11 Block diagram for non-contact distortion measurement device hardware depicting computer interface with major components.

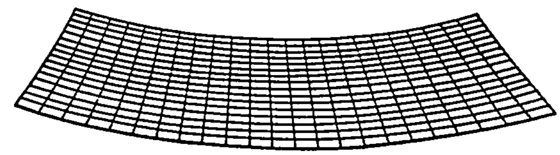
Computer Hardware/Software. Figure 11 depicts a block diagram of the major components and their relationships. Software-generated commands to each of the three NCMD motors are interpreted by stepping motor controllers which activate motor drivers for individual drive shaft positioning. A “frame grabber” interprets optical intensities detected by the CCD camera and provides an electronic image for software interpretation and computer monitor display if desired. Individual circuit boards house each controller and the frame grabber within the personal computer. Power supplies are located -in a cabinet adjacent to the computer.

The NCMD control program primarily consists of interrelated motor commands, image commands, and an automated mode which is executed by user-defined text files. A separate program provides for computer graphics representations of measured contours. During the measurement process, elevations as a function of their x,y positions are automatically stored in a user-named file. Values in such a file may be retrieved for hardcopy listing or accessed via the graphics routine to display a three dimensional representation of the specimen on the computer monitor.

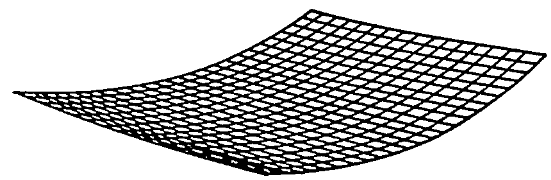
Figures 12 and 13 are reprints of such representations based on actual non-contact measurements of laser-formed “dish” and “sine” plate shapes. Note from the figures that the graphics routine allows specification of viewing angles from both the horizontal (specified value of "θ") and vertical (specified value of "ϕ") perspectives.



DISH(VIEWING ANGLE: $\theta = 210°$; $\phi = 60°$)



DISH(VIEWING ANGLE: $\theta = 180°$; $\phi = 70°$)



DISH(VIEWING ANGLE: $\theta = 130°$; $\phi = 70°$)

Fig. 12 Computer graphics representation of dish shape measurement using the non-contact distortion measurement device.

Limitations. Within the specified design considerations, major limitations of the NCMD may be grouped as either mechanical or programmatic in nature and represent the current state of device refinement.

1. Specimen Size. While theoretically there is no practical minimum size, maximum dimensions are dictated by the vertical separation distance between the device and a specimen and the extent to which the camera/mirror motor frame can be rotated by the x and y-axis scanning motors

2. Specimen Orientation/Position. As discussed, specimens must be placed below the NCMD. The present device is not designed to be portable.

3. Least Discernible Change in Elevation. Although the intervals between successive elevation measurement sites are adjustable via control software, the angular increment of mirror motor rotation will ultimately determine whether or not a change of elevation is sensed. Currently, elevation differences on the order of 0.01″ are detectable.

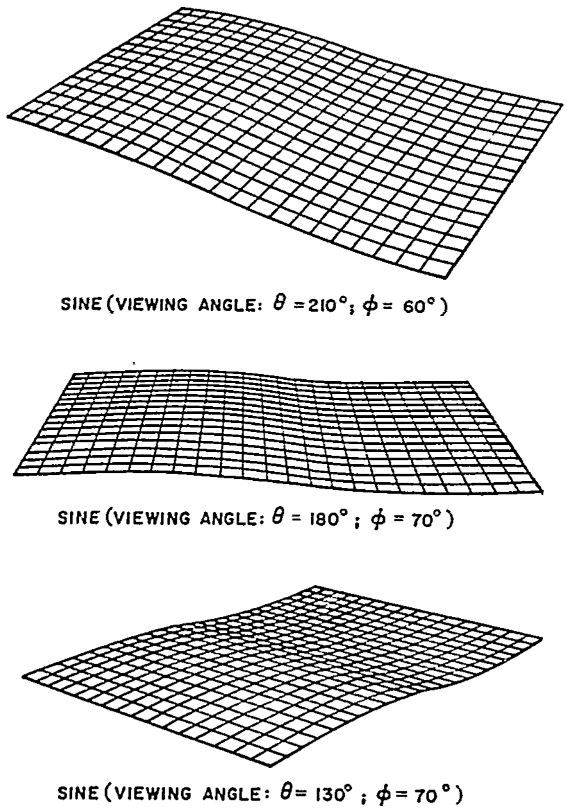


Fig. 13 Computer graphics representation of sine shape measurement using the non-contact distortion measurement device.

4. X-Axis Drive Motor Torque. To scan the entire width of a plate in the x direction, the x-axis drive motor must rotate the aluminum frame which houses the CCD camera and zoom lens, 45° angle mirror, mirror motor and mirror assembly, and the helium-neon laser tube. The motor torque required to accurately position this assemblage is slightly greater than the present motor's capability. Consequently, slight differences between the commanded and actual motor shaft position may arise during the measurement process, especially as the frame assembly is rotated farther from its initially-horizontal reference position. Since elevation calculations are based on expected (commanded) x-axis motor shaft positions, this is a potential source of measurement error. The condition is considered temporary based on several feasible modifications proposed for the present design.

5. Process Time Required for Plate-wide Measurement. This is the most critical shortcoming of the prototype and is a programmatic problem. At issue here is that the device requires approximately one minute to determine elevation at each measurement site. A majority of each such processing interval is devoted to mirror motor positioning of the laser spot at the computed centroid of the CCD camera's optical image area. Obviously, when many measurement sites are required, e.g. to examine surface countours in detail or when analyzing a large plate specimen, total process time can become excessive.

Measurement Method #3: Contact Distortion Measurement Device

Motivation. Extensive experiments in laser line heating were conducted by MIT researchers beginning in 1984 at laboratories in Washington, DC and 1985 in Hartford, CT. Proposed rapid expansion of a laser-powered thermo-mechanical plate bending data base during these studies dictated that a portable means of rapid yet accurate plate distortion measurement was needed. To fill the gap between slow and error-prone methods involving magnetic-base dial indicators and the relatively slow or inflexible methods previously described (from a plate-wide contour measurement perspective), a device dependent on specimen surface contact was developed(4).

Design Considerations. In addition to the factors listed in the preceding considerations for the NCMD, three more design requirements were mandated.

1. Independent from Specimen Orientation. As would be ideal in an actual production mileau, a deliberate attempt was made to develop a measurement technique not constrained to a particular fixed reference point. For example, if the magnitude of out-of-plane distortion of a vertical steel bulkhead needed to be determined, it may not be feasible to align such a structure with a vertical or horizontal reference frame. Conversely, it may be excessively time consuming to set up a measurement system if its accuracy or ability depended on a similar alignment.

2. Remote Operation Capability. Whether in the laboratory or workplace, the unwieldy nature of steel plating dictates that deflection measurements should occur on-location. Moreover, the measurement device should not be constrained by its necessary proximity to ancillary equipment.

3. Portability. Proper assessment of plate shape may require a number of repetitive deflection measurements using a device which relies on specimen contact.

Thus, the size and weight of the intended device were expected to be compatible with frequent operator repositioning. Additionally, the dimensions and weight of the device and any peripheral equipment were to be strictly minimized so that on-site transport or relocations between forming facilities were feasible if required.

Principles of Construction and operation. To remain compatible with the design limitations imposed, measurement of local radii of curvature via direct surface contact was undertaken. The well-known geometric tenet that a distinct circle is defined by any three points on its perimeter was selected as the design basis for this decision. Figure 14 illustrates this principle with a choice of three locations on the surface of a deformed plate. There the Greek symbol, "rho", denotes a unique radius of curvature prescribed by the local surface contour.

Application of this strategy involved using a rigid frame fitted with "legs" whose lengths could vary based on the shape of the contacted surface. Shown in Figure 15 is a side view of the frame atop a distorted plate. With this concept, the length of the center leg is fixed while each side leg length is adjusted for contact. Comparing side leg lengths with the "reference" center leg (lengths LA and RC vs. the fixed center length) and through the appropriate trigonometric relationships, the critical lengths TL = TB = TR = radius of curvature can be determined.

To carry out the above measurement strategy, eight identical rectilinear,

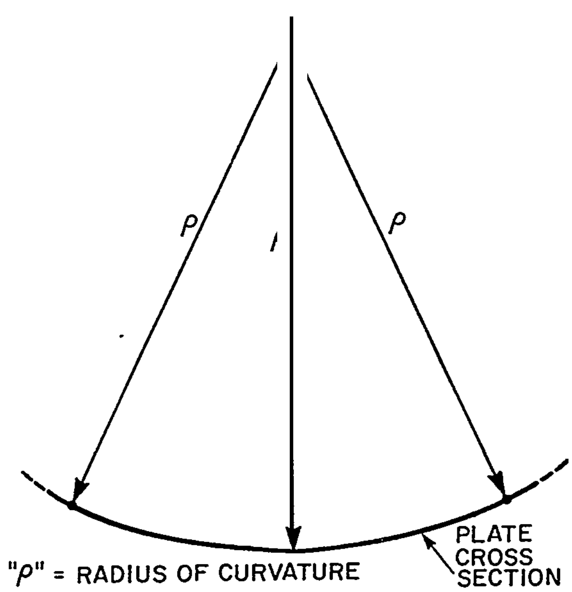


Fig. 14 Geometric principle for plate distortion measurements

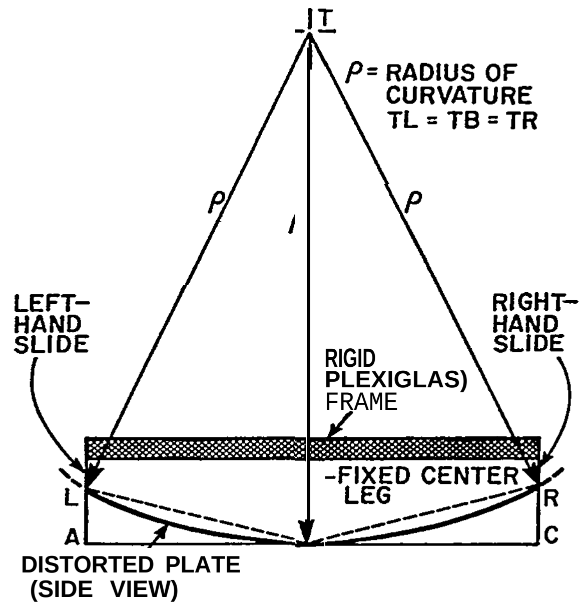


Fig. 15 Application for radius of curvature measurements

direct current, spring-loaded sliding potentiometers were positioned circumferentially (at 45° angles) and parallel to each other on a 3/4" thick, octagon-shaped piece of plexiglas. Figures 16 and 17 depict top and side views of the device respectively. The fixed-length center leg is more visible in the latter photograph.

Taking advantage of their uniform spacing, diametral pairs of potentiometers were chosen to coincide with the major points of a compass, i.e. north-south, northeast-southwest, etc. This permitted curvature measurements in fou

Fig. 16 Top view of contact distortion measurement device. (Illustration positioning of potentiometers around perimeter of plexiglas frame) .

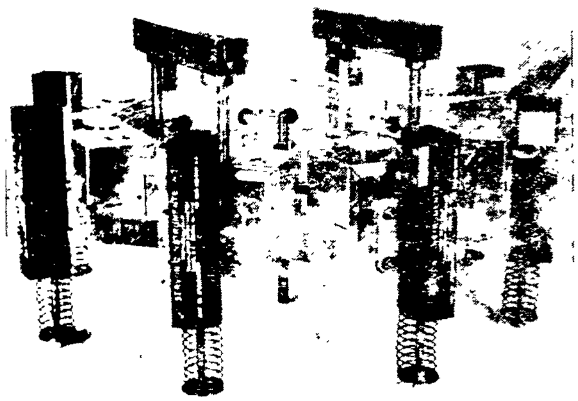


Fig. 17 Side view of contact distortion measurement device. (Illustrates spring-loaded potentiometer slides, fixed center leg, and control button on underside of right handle.)

major directions (using diametrically opposed potentiometers) and standardized device orientation during measurements in multiple locations.

Adjacent to each potentiometer housing, a small aluminum box contains circuitry necessary for potentiometer operation and (electric) calibration. Visible in Figure 16 on the right side of the "0" numbered box is a socket which enables the device to be connected to an AT&T PC 6300 personal computer via multi-conductor umbilical cabling.

The slide position of a potentiometer is determined by the voltage value sensed between a selected pair of its internal contacts. Through cabling, slide voltages become input values for an eight-channel analog-to-digital converter located within the computer. At the converter, analog voltage values are supplanted by their digitized equivalents, the latter of which are used in computer software routines to generate desired radii of curvature values. For remote operation and as shown in Figures 17 and 18, a small push-button trigger is installed in the underside of the right handle. When depressed, its circuitry initiates a round of software-controlled analog to digital conversions. Atypical conversion requires about 25 microseconds.

Through an appropriate choice of software routines written for the device, either curvature or radius of curvature at a specific location in a specific orientation can be determined. When the device is positioned for measurement and a measurement sequence is triggered, the results (in either hard-copy or computer monitor format) are available in approximately two seconds.

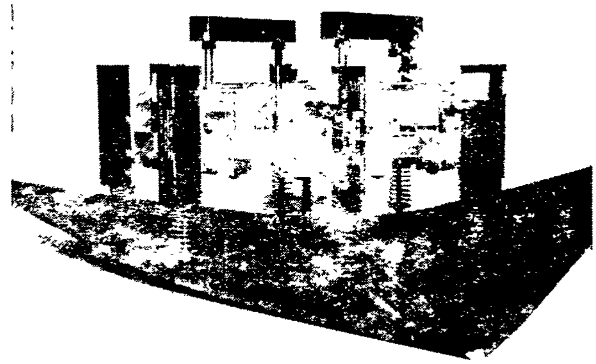


Fig. 18 Measuring distortion' of a steel plate specimen with tile contact measurement device. (Note variation in potentiometer slide lengths to conform with the specimen's surface topography.)

Limitations/Sources of Error. Note that in its present form, the contact measurement device (hereafter referred to as "Octopus" due to its eight "legs") is totally functional and was used extensively throughout MIT laser line heating research. However, as with any prototype, a list of operability conditions/restrictions exists. A majority of the known limitations of the "octopus" stem from mechanical factors. As with the NCMD, the following summary not only better defines its capabilities but indicates areas of potential future refinement.

1. Minimum Measurable Radius of Curvature. Based on the absolute range of travel of the potentiometers chosen, the minimum radius of curvature is about +14". (The smallest radius of curvature denotes the greatest amount of locally measurable distortion.) The minimum measurable radius of double curvature is +28" (coexisting concavity and convexity such as with a "saddle" shape) . These dimensions are well within the degree of bending required in ship production.

2. "Flat Plate Conditions. The radius of curvature for a plane is infinite. However, based on the (installed) analog-to-digital converter resolution, radii of curvature in excess of 25,000" cannot be accurately determined. To put this limitation in perspective, the edges of a four-foot wide plate whose shape conforms to this degree of curvature would be elevated approximately 0.02 inches above a horizontal reference frame placed at plate center.

3. Plate Contact. The Octopus will not work accurately if positioned so that the legs do not make contact with a specimen's surface. Moreover, although not critical, the best accuracy is achieved when the plane of the plexiglas is kept as parallel as possible to the surface being measured.

4. Computer Locale. Presently, a 25′ cable connects the Octopus to a personal computer. Future applications may dictate that this length be modified for a greater expanse of work area.

5. Smooth, Slowly Varying Plate Contours. Because the device depends on discrete samplings of plate elevation, surface anomalies will not be detected. Further, where such anomalies exist, care should be taken not to position potentiometer slides at their location(s) if the overall (general) degree of curvature is desired. With the contours inherent to ship production and those examined in line heating experiments, this appears to be an insignificant limitation.

6. Analog-to-Digital Resolution. Based primarily on analog-to-digital converter limitations, the smallest discernible change in potentiometer slide deflection is approximately 0.0011 inches.

7. Miscellaneous. Two potential sources of error outside absolute system resolution are associated with improper mechanical calibration and the moment-curvature effects of plexiglas flexure during measurement. For the former, precision laboratory measurements subsequent to a detailed calibration sequence indicated that cumulative slide movement errors could be kept within 0.001″. A similar degree of error is predicted by a worst-case scenario analysis regarding the effects of finite plexiglas frame rigidity.

Special Purpose Adaptations. Aside from numerous potential uses of the Octopus as presently configured, two additional applications are currently under investigation in an effort to extend its future utility. The first involves a “distortion matrix” concept; the second envisions its role as an intermediary in the development of an in-process distortion measurement system.

A distortion matrix (the term was coined at MIT during laser line heating research) is a mathematical representation of a distorted surface and is constructed to represent actual distortion from a prescribed frame of reference. For example, considering a particular steel plate, matrix “size” corresponds to actual surface area. Essentially, each matrix grid element represents the degree of distortion over a localized area of the plate. The number of matrix elements hence determines the resoluticm (accuracy) by which the matrix represents actual distortion.

To construct a distortion matrix for a surface of known dimensions using the Octopus, the number of elements must be chosen; e.g. a 3′ x 3′ plate could be represented by a 3 x 3 distortion matrix whereby each element would mathematically represent one square foot of plate surface. The Octopus would be positioned on each “element” of the plate to assess local contours while ensuring that Octopus axes (north-south, etc.) remain parallel among all measurement sites. Data from each triggered measurement would be stored in corresponding elements of the (mathematical) distortion matrix, thereby ultimately recording contours over the entire plate. Where little contour variance occurs (along a particular direction) it would not be necessary to physically place the Octopus at all element sites. In this situation, a distortion contour could be extrapolated fromor interpolated between actual measurement sites. Measurement site quantities could be further reduced by symmetry arguments where possible.

When complete, a distortion matrix would consist of an assemblage of local contours which, in the aggregate, represent the extent of plate-wide distortion. Implicit and fundamental to the accuracy of this method is contour continuity between adjacent matrix elements just as exists on the actual plate surface. A natural and simple extension of such known contours would be deflection determination at any desired location on the plate’s surface (relative to either another location or an established reference frame).

A straightforward second alternative for future Octopus use may be its role in the development of an automated plate bending facility. Although as previously discussed, non-contact measurement would be more ideal, the inherent simplicity and speed of the Octopus at this juncture makes it well suited to provide rapid measurement feedback during a bending iteration process. This may be particularly valid as an interim measure while other components and interfaces of the system are being developed and evaluated.

Current Contact Measurement Device (Octopus) Applications

Because of the success to date in using the Octopus for distortion measurement and its overall versatility, a summary of its applications both in the

laboratory and from a ship production perspective is considered warranted.

Research Applications. Three areas, as previously indicated, include:

1. Line Heating Data Base Development. Steel plate bending behavior as a function of heat input, plate thickness, material properties, etc. , can be characterized by evaluating distortion perpendicular to and along the direction of single heating passes or combinations of passes.

2. Contour Inputs to an Automated Plate Forming System. Via the distortion matrix concept, the desired degree of overall bending can become a system input by using the Octopus to measure a prototype surface which exhibits an arrangement of desired surface contours. Such a surface could easily be constructed of cardboard, wood, plastic, etc., with minimum cost and fabrication time.

3. In-Process Feedback During Automated Plate Forming. Again via the distortion matrix concept, the Octopus would provide an input for system comparison with the desired shape, thereby initiating or terminating an interative bending process.

Shipyard/Ship Production Applications.

1. Distortion Measurement. Because of its portability and independence from a required reference frame, the Octopus could be used to accurately assess distortion in virtually any shipboard or fabrication facility location. This ability may be particularly desirable for achieving required tolerances in weld distortion. removal or conversely, in rapidly determining whether a die stamped or rolled plate is properly formed.

2. Fit-up Assessment. The need to make on-site adjustment to plate sections prior to butt welding may be reduced through better accuracy control throughout the pre-fabrication process.

3. Die Construction. The Octopus could not only assist in determining die shape accuracy but also streamline the process of constructing a wide variety of dies

4. Damage Assessment. When collision damage occurs or when other structural deterioration results from heavy weather, fire, etc., in some situations, the degree of damage to a bulkhead, deck or outer hull plating can be rapidly quantified for repair calculations by use of a versatile contact measurement device. Additionally, knowing the absolute amount of distortion could be of assistance in selecting the most efficient repair strategy.

5. Line Heating Training Aid. Apprentice line heating technicians could be provided with near-instantaneous feedback on the results of a particular application of oxy-acetylene torch heat by using a device such as the octopus. This procedure would assist in identifying the most effective line heating procedures under a given set of heating conditions as well as eventually minimize unintentional line heatinq errors and the attendant iterations required to correct them.

Conclusions

Three novel distortion measurement methods have been presented along with particular applications and limitations for their use in a ship production environment. The ultimate pursuit of this and follow-on related research will continue to be toward the advancement of present day ship fabrication processes. As is evident in this paper, these measurement techniques should contribute to current expertise in the field as well as future automation efforts.

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